

## SCIENCE WITH ASKAP

### The Australian Square-Kilometre-Array Pathfinder

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## Abstract

The future of cm and m-wave astronomy lies with the Square Kilometre Array (SKA), a telescope under development by a consortium of 17 countries. The SKA will be 50 times more sensitive than any existing radio facility. A majority of the key science for the SKA will be addressed through large-area imaging of the Universe at frequencies from 300 MHz to a few GHz.

The Australian SKA Pathfinder (ASKAP) is aimed squarely in this frequency range, and achieves instantaneous wide-area imaging through the development and deployment of phase-array feed systems on parabolic reflectors. This large field-of-view makes ASKAP an unprecedented synoptic telescope poised to achieve substantial advances in SKA key science. The central core of ASKAP will be located at the Murchison Radio Observatory in inland Western Australia, one of the most radio-quiet locations on the Earth and one of the sites selected by the international community as a potential location for the SKA.

Following an introductory description of ASKAP, this document contains 7 chapters describing specific science programmes for ASKAP. In summary, the goals of these programmes are as follows:

- The detection of a million galaxies in atomic hydrogen emission across 75% of the sky out to a redshift of 0.2 to understand galaxy formation and gas evolution in the nearby Universe.
- The detection of synchrotron radiation from 60 million galaxies to determine the evolution, formation and population of galaxies across cosmic time and enabling key cosmological tests.
- The detection of polarized radiation from over 500,000 galaxies, allowing a grid of rotation measures at  $10'$  to explore the evolution of magnetic fields in galaxies over cosmic time.
- The understanding of the evolution of the interstellar medium of our own Galaxy and the processes that drive its chemical and physical evolution.
- The high-resolution imaging of intense, energetic phenomena by enlarging the Australian and global Very Long Baseline networks.
- The discovery and timing of a thousand new radio pulsars.
- The characterization of the radio transient sky through detection and monitoring of transient sources such as gamma ray bursts, radio supernovae and intra-day variables.

The combination of location, technological innovation and scientific program will ensure that ASKAP will be a world-leading radio astronomy facility, closely aligned with the scientific and technical direction of the SKA. A brief summary chapter emphasizes the point, and considers discovery space.

This astro-ph submission contains only an outline of the entire document published by Experimental Astronomy. You can download the full article from  
<http://www.atnf.csiro.au/projects/askap/newdocs/askap-expast08.pdf>

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## 1 Introduction

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The Australian SKA Pathfinder (ASKAP) is a next generation radio telescope on the strategic pathway towards the staged development of the Square Kilometre Array (SKA; see Schilizzi et al. 2007 for preliminary SKA specifications). The ASKAP project is international in scope and includes partners in Australia, Canada, the Netherlands and South Africa. This document, which concentrates on the science made possible with ASKAP was written as a joint collaboration between Australian and Canadian research scientists.

ASKAP has three main goals:

- to carry out world-class, ground breaking observations directly relevant to the SKA Key Science Projects,
- to demonstrate and prototype the technologies for the mid-frequency SKA, including field-of-view enhancement by focal-plane phased arrays on new-technology 12-metre class parabolic reflectors,
- to establish a site for radio astronomy in Western Australia where observations can be carried out free from the harmful effects of radio interference.

ASKAP is part of the Australian strategic pathway towards the SKA as outlined in the Australian SKA Consortium Committee’s “SKA: A Road Map for Australia” document. ASKAP is seen as ‘...a significant scientific facility, maintaining Australia’s leading role within the SKA partnership and addressing key outstanding computational/calibration risk areas ...’. SKA programs were given the highest priority for Australian radio astronomy in the 2006–2015 Decadal Plan for Astronomy.

In Canada the partnership in development and construction of ASKAP forms part of the Canadian SKA program, funded as part of one of the top priorities for future facilities in the Canadian Long Range Plan for Astronomy. In November 2006 the President of National Research Council of Canada and the Chief Executive Officer of the CSIRO signed an agreement declaring their intention to collaborate in the realization of ASKAP.

## 2 Extragalactic H I Science

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### 2.1 Summary

Understanding how galaxies form and evolve is one of the key astrophysical problems for the 21st century. Since neutral hydrogen (H I) is a fundamental component in the formation of galaxies, being able to observe and model this component is important in achieving a deeper understanding of galaxy formation. Widefield H I surveys using the next generation radio telescopes such as ASKAP and ultimately the SKA will allow unprecedented insights into the evolution of the abundance and distribution of neutral hydrogen with cosmic time, and its consequences for the cosmic star formation, the structure of galaxies and the Intergalactic Medium. ASKAP will provide powerful tests of theoretical galaxy formation models and improve our understanding of the physical processes that shaped the galaxy population over the last  $\sim 7$  billion years.

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### 3 Continuum Science

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#### 3.1 Summary

Understanding the formation and evolution of galaxies and active galactic nuclei (AGN) as a function of cosmic time is one of the most intensely investigated issues in contemporary astronomy, and is a key science driver for next-generation telescopes such as SKA, ALMA and ELTs. Today's instruments already give profound insights into the galaxy population at high redshifts, and a number of current surveys (e.g. ATLAS, ELAIS, GOODS, COSMOS) are asking questions such as: When did most stars form? How do AGNs influence star and galaxy formation? What is the spatial distribution of evolved galaxies, starbursts, and AGNs at  $0.5 < z < 3$ ? Are massive black holes a cause or a consequence of galaxy formation?

However, most of these surveys are primarily at optical and IR wavelengths, and can be significantly misled by dust extinction. Radio observations not only overcome dust extinction, but also provide data on AGN that are unavailable at other wavelengths. ASKAP will be able to determine how galaxies formed and evolved through cosmic time, by penetrating the heavy dust extinction which is found in AGN at all redshifts, and studying the star formation activity and AGN buried within.

## 4 Polarization Science

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### 4.1 Summary

ASKAP will be both a technical and scientific pathfinder to the Square Kilometre Array. One of the five key-science drivers for the SKA is to understand the origin and evolution of cosmic magnetism. The prime observational approaches to this key science will be a deep survey of polarized emission from compact extragalactic sources (Beck & Gaensler 2004), and of the diffuse polarized radiation from the Galaxy. This data set will provide

- a deep census of the polarization properties of galaxies as a function of redshift (secured through complementary H I or optical surveys),
- a dense grid of Faraday rotation measures to over 500,000 background radio sources
- all-sky Faraday Rotation image of the 3-dimensional structure of the diffuse magnetized medium of the Galaxy.

The Rotation Measure (RM) of a polarized radio signal is derived from the variation in wavelength of the polarization angle of linearly polarization,  $\phi$ , given by

$$\phi = \phi_0 + \lambda^2 0.812 \int n_e \mathbf{B} \cdot d\mathbf{l} = \phi_0 + \lambda^2 \text{RM} \quad (1)$$

where  $n_e$  [ $\text{cm}^{-3}$ ] is the electron density and  $\mathbf{B}$  [ $\mu\text{G}$ ] is the magnetic field along the propagation path  $d\mathbf{l}$  [pc]. A dense, all-sky grid of RM values to background radio sources and all-sky images of the RM of the polarized emission from the Galaxy, are thus powerful and unique probes of cosmic magnetism in the Milky Way Galaxy, the intergalactic medium, and in extragalactic radio sources.

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## 5 Galactic and Magellanic Science

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### 5.1 Summary

The rebirth of observational studies of the Milky Way and Magellanic System over the past decade has raised new and profound questions about the evolution of the interstellar medium (ISM). The community has transitioned from studying small-scale aspects of the ISM to a more wholistic approach, which seeks to combine information about a variety of ISM phases with information about magnetic fields. With ASKAP we can make significant and unique inroads into understanding the evolution of the ISM and through that the evolution of the Milky Way. These are crucial steps along the path to understanding the evolution of galaxies.

The Milky Way and Magellanic System because of their very large sky coverage can only be observed in survey mode. As such, they present themselves as ideal targets for ASKAP. Here we discuss how ASKAP can be used to achieve superb advances in our understanding of the evolution of the Milky Way, its ISM and its magnetic field. To achieve these advances we propose several large-scale projects, which include: accounting for and studying the structure of all H I associated with the Milky Way and Magellanic System to unprecedented column-density limits and angular resolution; constraining the large-scale Galactic magnetic field in the inner Galaxy with *in situ* measurements of H I Zeeman splitting; exploring the growth of molecular clouds using diffuse OH mapping of the Galactic plane; and probing the turbulent magneto-ionic medium of the Galactic halo with diffuse continuum polarization mapping of the whole sky. The unifying technological requirement for all aspects of the Galactic and Magellanic science presented herein is the demand for low-surface-brightness sensitivities achieved by compact configurations.



## 6 Very Long Baseline Interferometry Science

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### 6.1 Summary

We describe possible areas of science that can be addressed using VLBI and ASKAP. A number of scientific programs present themselves when considering the use of ASKAP as part of the Australian Long Baseline Array (LBA) and the global VLBI array. Better angular resolution at L-band, better sensitivity, and better  $uv$  coverage will aid standard VLBI observations of AGN, pulsars, and OH masers. An innovative additional capability for ASKAP is multibeaming. If this can be harnessed for VLBI in the form of multiple phased array beams, a number of wide-field survey observations become feasible.

In time, ASKAP should also become part of the recently developed Australian e-VLBI network, currently called PAMHELA. An interesting possibility is to not use ASKAP as part of the LBA, but use it as a source of trigger information for radio transients, as part of ASKAP survey work. These triggers could be transmitted to PAMHELA, and the candidate sources targeted at high angular resolution in rapid follow-up observations. The combination of ASKAP and PAMHELA would be unique and powerful. PAMHELA would add great scientific value to the low resolution detection of transients by ASKAP.

At this point the VLBI community supports the extension of the ASKAP frequency range to S-band (2.4 GHz) but recognises several alternatives to this that may be more cost effective, such as the upgrade of the Ceduna antenna to L-band and/or the use of one of the AuScope geodetic antennas in WA at S-band. All these options should be studied at greater length. The addition of antennas to ASKAP beyond the current plans will make for a more sensitive VLBI array but will not materially open up new areas of science for VLBI.

## 7 Pulsar Science

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### 7.1 Summary

Since the initial discovery of pulsars in Cambridge (Hewish et al. 1968), radio telescopes world-wide have played a major part in the discovery of new pulsars. Pulsars have been used as tools to address some of the most fundamental questions in basic physics, allowing precision tests of general relativity, investigations into the equation of state of ultradense matter and the behaviour of matter and radiation in the highest magnetic fields known in the universe. The commissioning of ASKAP will provide the transition between the use of large single-dish instruments (such as the Parkes and Arecibo telescopes) to using large numbers of small antennas with a wide field-of-view (FoV) as is likely in the final mid to high frequency SKA design.

Applications of pulsar observations include a very wide variety of interesting astrophysical topics, often with unparalleled precision. Such topics include binary evolution, binary dynamics, the interstellar medium, globular cluster physics, supernova remnant astrophysics, the physics of relativistic winds and precision astrometry. Pulsars are also intrinsically interesting, being the result of core collapse supernovae and astonishing converters of mechanical energy of rotation into electromagnetic radiation, particles and magnetic fields. The study of pulsars themselves is important for constraining the overall population's properties and hence their origin, as well as understanding the mysterious pulsar emission mechanism.

Historically it has been common to carry out pulsar research using large single dish instruments. ASKAP provides a pathway between the current systems and the full-scale SKA. ASKAP will be ideal for carrying out relatively fast all-sky surveys that will allow  $\sim 1000$  pulsars to be discovered. In this chapter, we show that it will be possible for ASKAP to continue to observe these (and previously known) pulsars in order to determine their astrometric, spin and orbital parameters. ASKAP will, for several millisecond pulsars, be able to provide data suitable for integration into a global timing array project which aims to detect low-frequency gravitational wave sources.

Pulsar observations, especially searches, with ASKAP will present several logistical and computational challenges, some of which can be mitigated through specification choices. In particular, any large-scale survey with good sensitivity will be severely limited computationally; the need to process every pixel independently ensures that this will become worse as the square of the maximum baseline length. It is therefore necessary that as many short baselines as possible be present in the configuration of ASKAP. For pulsar timing, there is no such requirement; any configuration is adequate.

The expansion of ASKAP would be good for several reasons. Most important is the increase in instantaneous sensitivity through both the addition of more telescope collecting area and a reduction in system temperature. These will ensure that ASKAP will become more competitive in searching and in high precision pulsar timing, leading to improved data-sets for inclusion in global timing array projects. More array elements will also ensure that more short baselines are present in the array.

## 8 The Transient and Variable Radio Sky

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### 8.1 Summary

The good sensitivity and large field-of-view make ASKAP a unique instrument for studying radio transients and variables. We strongly expect that ASKAP will make a unique discovery in the transient parameter space, although it is naturally hard to predict the nature of a new class of transients.

The key to a successful transient instrument is that it have high sensitivity, large field-of-view, good dynamic range and high resolution. ASKAP fulfills these criteria with its ability to achieve sub mJy sensitivity across the entire sky in a single day observing. Nearly all transients arise from point source objects; high resolution is ideal for obtaining accurate positions necessary for follow-up at other wavebands. It is important also that a wide range of timescales from seconds to months are covered by the transient detector. This implies a careful search strategy for uncovering rare objects.

ASKAP will most likely suffer from a surfeit of transient and variable sources. This will pose challenges both for imaging and for determining which sources are most interesting and worthy of follow-up observations on other facilities. Chapter 6 describes some possible mechanisms for VLBI follow-up of transient sources.

## 9 Summary

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Most of the phenomena we observe today, using telescopes to observe across the electromagnetic spectrum, were unknown a few decades ago. *Most were discovered by radio astronomers using increasingly powerful instruments; see the list by Wilkinson et al. (2004).*

In “Cosmic Discovery”, Harwit (1981) addresses the question of what factors lead to new discoveries in astronomy. He argues that a large fraction of the discoveries have been associated with improved coverage of the electromagnetic spectrum or better resolution in the angle, time, or frequency domain. He also notes that astronomical discovery is often closely linked to new technology introduced into the field. Wilkinson et al. (2004) detail just how it is that SKA will extend the multi-dimensional observing space, and they describe considerations in design and operation that are important to enable discovery of the unexpected. These latter precepts are equally vital for the design and operation of ASKAP.

ASKAP is the first of a new generation of radio telescopes using innovative phased-array feed technology to explore a greatly enlarged survey-area parameter space. This wide field of view – a major step along the SKA path – is essential for many of the science cases presented here. But following Harwit and Wilkinson et al., we can anticipate it leading to the discovery of new, rare and unexpected phenomena. As pointers to this, Section 2.9 describes one recent and unexpected discovery, while Section 8.8 presents an unusual proposal which would open a new field of particle astrophysics to astronomers. One explores the capabilities of highest frequency resolution; the other the possibilities of using the highest time resolution.

These exciting possibilities spotlight advancing radio astronomy: ASKAP is a key step on the strategic pathway towards the SKA. The goals of ASKAP, simply stated, are to carry out world class, ground-breaking observations, to demonstrate and prototype technologies for the mid-frequency aspect of SKA, and to establish a site for radio astronomy in Western Australia where observations can be carried out free from the harmful effects of radio interference.

This paper has set out the main science themes to be tackled by ASKAP, themes which play into the major issues confronting astrophysics and cosmology today and which naturally parallel those outlined as science drivers for the SKA: the formation, evolution and population of galaxies including our own, understanding the magnetic universe, exploring the poorly-understood transient radio sky, and directly detecting the gravitational waves which must permeate our Universe.